Systems Thinking Research in Science and Sustainability Education: A Theoretical Note

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1. Introduction

The current global problems related to climate change, energy, environment and economic inequality are complex and systemic problems, which require systemic solutions (Capra and Luisi 2014). These problems are not only the subject of science, but also the subject of geography, philosophy, economy and history (Booth-Sweeney 2017). For a sustainable world, all these problems need to be addressed together, considering the social, economic and environmental aspects of sustainability (National Research Council (NRC) 2012). At this point, education plays a crucial role to shape individuals' knowledge, skills, and attitudes to be responsible citizens for a sustainable world. The Sustainable Development Goals (SDG) adopted at the United Nations (UN) Sustainable Development Summit emphasize that all learners should acquire the necessary knowledge and skills for sustainable development until 2030. Seventeen SDGs highlight the main themes of sustainable development, which are justice, peace, equity, and gender (Osman et al. 2017). SDG 4 underlines that all people should have equal access to education and promotes lifelong learning opportunities for all people (United Nations UN). It is important to develop teachers' capabilities and increase the quality of education to deal with the complex problems of today. Particularly for children living in low-income countries, the fragile environment should be strengthened with the necessary knowledge and skills for sustainability. It is crucial to address poverty, climate change and inequality, which are interrelated problems whose solutions are interlinked (United Nations UN). Students and teachers should see these important issues as systems that interact and affect each other (Booth-Sweeney 2017). Systems thinking is a necessary tool to understand these problems and find solutions to them (Meadows 1991).

Systems thinking is a combination of different skills and is a higher order way of thinking (Ben-Zvi-Assaraf and Orion 2005; Senge 1990). Systems thinking is related to thinking in terms of connectedness, understanding relationships, patterns and contexts (Sterling et al. 2005). According to Senge (1990), it is a discipline to understand the complex systems and the interconnections among them. Systems thinking helps one understand how the whole system works, the fundamental reasons behind the problems, and how to find solutions to these problems (Meadows 2008). For instance, in order to understand climate change, we first need to understand how the climate works as a system, the social, political, and environmental factors affecting climate change and the relationships among these factors (Booth-Sweeney 2017). In a similar way, a watershed ecosystem includes the dimensions of a system and the relationships among them. The interconnection among geological, ecological, atmospheric and hydrological systems is important for the sustainability of the earth system (Logan 2018). Furthermore, in order to achieve the Sustainable Development Goals, integrated, holistic and multidisciplinary approaches are required, which implies putting systems thinking into practice in education (Reynolds et al. 2018).

Systems thinking has received the increasing attention of educators in recent years and has been investigated in different disciplines such as science education (e.g., Batzri et al. 2015; Brandstadter et al. 2012; Riess and Mischo 2010), biology education (e.g., Fanta et al. 2019; Zangori and Koontz 2017), engineering education (e.g., Gero and Zach 2014), and sustainability education (e.g., Ateşkan and Lane 2018; Connell et al. 2012; Sandri 2013; Remington-Doucette et al. 2013). In these studies, different research methods, measurement tools, instructional strategies and different systems thinking models have been used. Moreover, systems thinking has been investigated in various fields of study, such as ecosystems, climate change, energy transfer, and the groundwater systems (e.g., Evagorou et al. 2009; Pan and Liu 2018; Shepardson et al. 2014).

In science education, understanding complex systems and their functions requires systems thinking (Pan and Liu 2018). National Research Council (NRC) identified science education standards and focused on the core ideas and cross cutting concepts. The NRC framework included the core ideas related to the complex structure of ecosystems and the dynamic relationships in ecosystems. The NRC framework further addressed systems thinking as a cross cutting concept of understanding systems and system models. Various studies have examined students' understandings of complex systems (Ben-Zvi-Assaraf and Orion 2005, 2010a; Jin et al. 2019; Puttick and Raymond 2018). Understanding complex systems is a challenging process. For example, climate change education is generally considered to be challenging because it includes complex structures which are difficult for students to understand (Orion and Ault 2007). First, students should understand the carbon cycle system in order to understand the impact of carbon dioxide accumulation in the atmosphere (Puttick and Raymond 2018). If students can perceive climate as a system, then they can gain a better insight into the connection between climate, climate change, environment and humans (Roychoudhury et al. 2017).

The systems thinking perspective is critical to understanding the interconnectedness in natural systems. In order to find solutions to sustainability problems, integration of knowledge about natural and human systems and collaboration between disciplines are needed (Remington-Doucette et al. 2013). Thus, systems thinking is regarded as a central component to achieve sustainability literacy (Nolet 2009) and the key competency that teachers should have in the field of sustainability education (UNESCO 2018). It is not easy to understand sustainability issues without a systems thinking perspective (Cloud 2005). Therefore, it is important to foster teachers' systems thinking skills so that they can create teaching strategies to enhance the systems thinking skills of their students (Lavi and Dori 2019).

In order to develop the systems thinking skills of students, different approaches and strategies have been proposed in several research studies. In a recent study, Schuler et al. 2018 designed courses to measure and improve pre-service teachers' systems thinking skills. They created a competence model and measured the four dimensions of systems thinking (declarative system knowledge, system modeling, solving problems using system models, and evaluation of system models). They revealed that pre-service teachers' systems thinking and their pedagogical content knowledge to teach systems thinking can be improved through teacher education programs.

Lavi and Dori (2019) also conducted a research study in order to foster and evaluate systems thinking skills of science and engineering pre-service and in-service teachers. They developed a method to create a common language, a shared terminology related to systems thinking for science and engineering teachers. Thus, they contributed to the literature methodologically by developing a valid and reliable rubric to assess systems thinking skills.

In another study, Brandstadter et al. (2012) examined the effectiveness of the concept mapping technique to measure students' systems thinking within the context of science education. The participants of their study were primary and secondary students and they found that computer-based concept mapping is an appropriate tool to make large scale assessments in systems thinking.

Research studies to facilitate and assess systems thinking skills in science and sustainability education have increased in recent years. It is important to examine these studies in terms of their research methodology and the systems thinking models that they used. In this way, similar and different aspects of these research studies can be explored, and the gaps in the literature can be identified to guide future studies.

Systems Thinking Models

Systems thinking has been investigated in various contexts, and different systems thinking models have been used. To be able to find a common framework for the systems thinking research, it is important to examine these models. In this part, systems thinking models used in the science and sustainability education context were presented briefly to understand the structure of these models. These models were categorized based on the dates when they were developed.

The system dynamics and systemic reasoning models were developed in the 1990s and used in educational research. Systems dynamics in education was first reported by Forrester (1992) and refers to learning by doing to change mental models (Forrester 2007). Through a systems dynamics approach, students develop problem solving skills and learn cause–effect relationships between concepts (Forrester 1992). Systems dynamics are related to integrating real life systems into computer simulation models to explore the complex structure of the systems (Forrester 2007). Systems thinking skills include dynamic complexity, positive and negative feedback processes, stock-flow relationships, recognizing delay, understanding their impacts and identifying non-linearities (Booth-Sweeney and Sterman 2000). Stock–flow relationships, feedback loops and relationships are considered aspects of systems dynamics (Nuhoğlu 2014).

Chandler and Boutilier (1992) developed a model related to systemic reasoning that includes four aspects. The authors argued that systemic reasoning is useful to understand open dynamic systems like ecological systems. The systemic reasoning model was used in recent research studies. Hokayem and Gotwals (2016) used four aspects of systemic reasoning to design learning progression within the ecological issues context. The four aspects of systemic reasoning determined by Chandler and Boutilier (1992) are as follows:

- *Systemic synthesis:* If an element of a system changes, the whole system is affected.
- *Systemic analysis:* Defining the elements of a system and recognizing the essential and non-essential elements.
- *Dynamic recycling:* Understanding how recycling in a system creates sustainability.
- *Circular connectivity:* Recognizing the feedback loops in a system.

Richmond (1991, 1993), who is an expert on systems thinking, described that individuals with a systemic perspective can see both the forest and the trees. The author noted the gap between the nature of the current problems of the world and our understanding of them. To reduce this gap, systems thinking should be understood well. Richmond (1993) suggested a systems thinking model that constitutes seven aspects, which are dynamic thinking, closed loop thinking, generic thinking, structural thinking, operational thinking, continuum thinking, and scientific thinking. These seven aspects show the multidimensional nature of systems thinking and each of them should be developed for better learning (Richmond 1993).

Hmelo-Silver and Pfeffer (2004) noted that it is important to recognize complex systems like ecosystems, in order to understand the interconnectedness of the world. For example, while learning ecological systems, it is necessary to envision how individuals, populations and communities interact with each other (Hmelo-Silver et al. 2007). In general, the characteristics of complex systems are difficult to understand. There are complex interactions among the components of complex systems, and these interactions are mostly nonlinear, including positive and negative feedback loops (Ben-Zvi-Assaraf and Orion 2005; Hmelo-Silver et al. 2007). If a change occurs in the components of a complex system, the stability of the whole system can be disrupted (Roychoudhury et al. 2017). These complex systems can be understood from different perspectives, like the systems dynamics model and the structure-behaviour-function (SBF) model (Hmelo-Silver and Pfeffer 2004). The SBF model formulates the essential principles to understand complex systems and allows understanding the structural elements in a system, the components of a system, the purpose of these components, and the mechanisms that enable the functioning of these components (Hmelo-Silver and Pfeffer 2004). In science education, students experience difficulties in learning complex systems (Ben-Zvi-Assaraf and Orion 2005). For example, they mostly learn simple linear relationships and visible components of ecosystems (Hmelo-Silver et al. 2007; Hogan 2000). In order to develop students' understanding of complex systems, computer-supported and hands-on activities have been suggested as useful tools (Ben-Zvi-Assaraf and Orion 2005, 2010a; Hmelo-Silver et al. 2015).

Ben-Zvi-Assaraf and Orion (2005) studied systems thinking in the field of earth system science and developed a structural hierarchical model to determine the characteristics of systems thinking. Orion (2002) maintained that understanding the earth's subsystems and their relationship with the environment requires understanding what science is. When students develop an understanding of water systems, they can understand the important role of water systems in global ecosystems (Ben-Zvi-Assaraf and Orion 2005). The authors listed eight emergent characteristics of systems thinking within the earth science context, as follows:

- The ability to identify the components of a system and processes within the system
- The ability to identify the relationships among the system's components

- The ability to organize the systems' components and processes within the framework of relationships
- The ability to make generalizations
- The ability to identify the dynamic relationships within the system
- The ability to understand the hidden dimensions of the system
- The ability to understand the cyclic nature of systems
- The ability to think temporally: retrospection and prediction

Ben-Zvi-Assaraf and Orion (2005) emphasized that a system thinker should first understand a system's components and interactions. In order to reduce environmental threats to earth systems, dynamic and cyclic relationships should be identified. Understanding the human impact on water cycle systems of using fertilizers and pesticides can be an example of understanding dynamic relationships. Moreover, according to the authors, there might be hidden dimensions of systems that might not be seen at the first glance. The authors, for instance, noted several questions for the water cycle system, such as "What is the cause of groundwater pollution?", "How can people be affected by that pollution?" and "How long can those chemicals stay in the rocks?". They suggested that these kinds of questions are needed to have backward- and forward-thinking skills. In other words, it is important to consider the impact of current problems on our future life.

Stave and Hopper (2007), on the other hand, suggested a model which includes a taxonomy of systems thinking. The authors developed this model based on the systems dynamics literature and the interviews with systems educators, in order to determine individuals' systems thinking levels. The authors categorized seven systems thinking components based on the levels of Bloom's taxonomy. These systems thinking components are recognizing interconnections, identifying feedback, understanding dynamic behaviour, differentiating types of variables and flows, using conceptual models, creating simulation models, and testing policies. These are the dominant systems thinking components which were derived from the literature.

Recently, Arnold and Wade (2015) compared various systems thinking definitions and determined different and common points. Then, the authors suggested a new definition for systems thinking that can be used in a variety of disciplines, focusing on the goals and elements of system thinking and the interconnections among these elements. The authors combined different elements of systems thinking, such as interconnections, feedback loops, stock and flow relationships, non-linear relationships and dynamic behavior, and stated that their systems thinking definition can be used in systems thinking research studies.

Within the scope of sustainability education, researchers focused on various systems thinking models, and discussed systems thinking as one of the key competencies of sustainability education (e.g., Sleurs 2008; UNECE 2011; Wiek et al. 2011). Sleurs (2008) defined systems thinking as recognizing that we are a part of the global system and understanding the relationship between environment, economy and society. Riess and Mischo (2010) defined systems thinking as "the ability to recognize, describe, model and explain complex aspects of reality as systems". Based on this definition, Fanta et al. (2019) designed the heuristic competence model of systems thinking within the sustainability education context. This model included four dimensions, which are "declarative system knowledge" (knowledge of different system properties), "system modeling" (understanding complex systems by system models), "solving problems using system models", and "evaluation of system models". This model was used to create effective approaches to develop the systems thinking skills of students and teachers. Furthermore, Karaarslan-Semiz and Teksöz (2020) determined twelve systems thinking skills, in the science and sustainability education context, based on the literature. The authors described some of these skills as identifying the components of a system; hidden dimensions; interrelationships among the social, economic and environmental aspects of sustainability; time dimension; recognizing personal role in the system, and the cyclic nature of the system. In order to improve the systems thinking skills of pre-service science teachers, the authors designed an outdoor education for a sustainability course, and they explored whether that outdoor education course could develop pre-service science teachers' systems thinking skills.

Some systems thinking models within the science and sustainability education context were examined and are presented in Table 1. Although these systems thinking models have similarities and differences, they are mostly based on the early definitions of systems thinking, such as that of systems dynamics by Forrester (1992) and the systems thinking approach by Richmond (1993). The systems thinking components proposed in these models are all important and interconnected. As seen in the analyzed articles, researchers have mostly used these models to design systems thinking interventions and assess the systems thinking skills of the learners.

Table 1. Systems thinking models derived from the literature.

	Systems Thinking Models
1.	Systems Dynamics Model (Forrester 1992)
2.	Richmond's (1993) Systems Thinking Approach
3.	Systemic Reasoning (Chandler and Boutilier 1992)
4.	Structure–Behavior–Function Model (Hmelo-Silver and Pfeffer 2004).
5.	A Structural Hierarchical Model of Systems Thinking (Ben-Zvi-Assaraf and Orion 2005)
6.	Taxanomy of Systems Thinking (Stave and Hopper 2007)
7.	Arnold and Wade's (2015) Systems Thinking Model
8.	Heuristic Competence Model (Fanta et al. 2019; Schuler et al. 2018)
9.	Systems Thinking as a Key Competency in Sustainability Education (Sleurs 2008; UNESCO 2018; Wiek et al. 2011)

Based on the discussion above, the author aimed to present the whole picture of systems thinking models in science and sustainability education and methodological and instructional insights related to systems thinking research. It is expected that this literature review will provide several directions for future research studies. The following research questions guided this study:

1. Which topics related to systems thinking have been studied within the context of science and sustainability education and the scope of primary, secondary and higher education?
2. Which systems thinking models have been used in systems thinking research studies?
3. Which research methods and data collection tools have been applied in systems thinking research studies?
4. What teaching strategies have been used to improve the systems thinking skills of students in primary school, secondary school and higher education levels?

2. Materials and Methods

This study aims to review the recent research studies on systems thinking in science and sustainability education. A systemic review was conducted in order to find appropriate articles for reviewing. In particular, the studies conducted in the past 10 years, from 2009 to 2019, were examined. Major journals in science education and sustainability education were found. In some journals, appropriate articles for this study could not be found; therefore, they were not included in the study. A search was conducted based on the terms systems thinking, science education, education for sustainability, education for sustainable development (ESD) and sustainability education. Most of the articles were written in English. Only two of the selected articles were written in Turkish. The articles were selected in terms of the following criteria:

- Scope: international and national research
- Type of research: empirical studies for measuring and developing systems thinking skills
- Years: 2009–2019
- Academic research articles published in peer reviewed journals
- Language: English and Turkish
- Target: students in primary, lower and upper secondary education and higher education (including student teachers)

The articles were divided into two groups: studies with and without intervention. Articles as theoretical notes and literature reviews about systems thinking were not included in the study. Consequently, 17 journals were selected and examined. In these journals, 32 articles fulfilling the above-mentioned criteria were analyzed. The selected journals and articles are presented in Table 2.

Table 2. Selected journals and analyzed articles.

Journals	Articles
Başkent University Journal of Education (Turkish)	(?)
Education Sciences	(Bernier 2017; Jeronen et al. 2017)
Educational Sciences: Theory and Practice (Turkish)	(Nuhoğlu 2014)
Environmental Education Research	(Golick et al. 2018; Rodriguez et al. 2014; Shepardson et al. 2014)
Eurasian Journal of Mathematics, Science and Technology Education	(Ben-Zvi-Assaraf and Orion 2009)
Journal of Biology Education	(Fanta et al. 2019; Jordan et al. 2014; Hokayem et al. 2015; Zangori and Koontz 2017)
Journal of Education for Sustainable Development	(Foley et al. 2017)
Journal of Environmental Education	(Tolppanen and Aksela 2018)
Journal of Geography in Higher Education	(Schuler et al. 2018)
Journal of Research in Science Teaching	(Ben-Zvi-Assaraf and Orion 2010a, 2010b; Hmelo-Silver et al. 2015; Hokayem and Gotwals 2016)
Journal of Science Education Technology	(Batzri et al. 2015; Puttick and Raymond 2018)
Journal of Sustainability Education	(Connell et al. 2012)
International Journal of Science Education	(Brandstadter et al. 2012; Riess and Mischo 2010; Evagorou et al. 2009; Pan and Liu 2018; Rosenkranzer et al. 2017)
International Journal of Science and Mathematics Education	(Puttick and Raymond 2018)
International Research in Geographical and Environmental Education	(Cox et al. 2019)
International Journal of Sustainability in Higher Education	(Remington-Doucette et al. 2013)
Research in Science Education	(Lee et al. 2019; Küçük-Doğanca and Saysel 2018)

Qualitative content analysis was performed to analyze the selected articles (Frankel and Wallen 2006). The articles were analyzed based on the categories of topics, systems thinking models, and research methodologies. The methodology sections of the articles were categorized in terms of sample, research design, data collection process, and instructional design (if there was an intervention). Each article was read several times by the author, and a data analysis table was constructed for each article. The selected articles were examined based on the above-mentioned categories. The following section presents findings of the data analysis.

3. Results

As stated earlier, the selected articles were analyzed based on the pre-determined categories, which are topics, systems thinking models and research methodologies. Coding tables were created for each article. Table 3 shows an example of the coding system of two articles.

Table 3. An example of the coding of the articles in terms of topic, systems thinking models and research methodologies (with and without intervention).

	Paper ID-14	**Paper ID-52**
Author and Year	Fanta et al. (2019)	Golick et al. (2018)
Title of the article	Fostering systems thinking in student teachers of biology and geography—an intervention study	A framework for pollination systems thinking and conservation
Journal	Journal of Biology Education	Environmental Education Research
Topics studied in the articles	Global problems (deforestation, soil degradation, overfishing, and climate change)	Pollination system
Systems thinking models	Heuristic structural competence model of systems thinking	Structure-Behaviour-Function Model
Sample	Student teachers	Undergraduate students
Research design	Quasi experimental intervention study	Qualitative inquiry
Intervention (Yes or No)	Yes	No
Data Collection Method	Achievement test (including both open ended and multiple-choice questions)	Structured interviews, open ended questions and prompts
Instructional design (if there is intervention)	Simulation software programs (computer-based education)	No

According to the content analysis results, three categories of topics framed the research studies, which are "complex systems", "sustainability issues and global problems" and "earth system science". The findings showed that the research content of 47% of the articles included sustainability issues and global problems, followed by complex systems and earth systems.

In terms of research methodologies, both qualitative and quantitative research designs were adopted in the selected articles. Notably, 53% of the articles included intervention in order to foster students' systems thinking skills. Moreover, 47% of the articles included descriptive studies such as assessing the current level of systems thinking skills of students. Notably, systems thinking researchers mostly preferred experimental and qualitative research designs.

Moreover, the selected studies included various participant groups from primary school to undergraduate level. Lower secondary school students were found to be the most studied sample (40%). It was observed that the number of studies conducted with primary school, upper secondary school and undergraduate students was limited. Moreover, both qualitative and quantitative data collection tools were used in the studies. In fact, systems thinking researchers mostly preferred written assessments (40%) and interviews (28%) to evaluate systems thinking levels of students. The authors were less likely to use quantitative measurement tools to assess systems thinking skills. Table 4 shows the analysis of the selected articles in terms of topics and research methodologies.

Lastly, systems thinking models used in the selected articles were examined. It was explored that systems thinking researchers used various systems thinking models. The most commonly used systems thinking model was the systems thinking hierarchical model developed by Ben-Zvi-Assaraf and Orion (2005). The model of understanding complex systems and emergent perspectives and the structure–behavior–function model were also used in the analyzed articles to explain complex systems. There are some similarities related to the components of systems thinking in these models. The dominant characteristics of systems thinking explored in the models were the identification of components of a system and the interconnections among these components, understanding the dynamic and cyclic relationships, identifying the feedback loops, recognizing the hidden dimensions, and exploring the impact of current practices on future practices (time dimension). All these characteristics of systems thinking have been described in systems thinking models. Table 5 summarizes the systems thinking models and the number of articles that used these models.

Instructional strategies most frequently used in the intervention studies were "inquiry-based learning", "game-based education", "problem-based learning", "computer simulation programs", "outdoor learning" and "group work". Among these instructional strategies, inquiry-based teaching and computer simulation programs were the most commonly used teaching methods to improve systems thinking skills. Moreover, researchers used different teaching strategies together. For instance, game-based education, computer simulation programs and inquiry-based education were applied together to foster students' systems thinking skills. Figure 1 shows the instructional strategies used in the analyzed articles.

Table 4. Analysis of the articles in terms of topics and research methods.

			Number of Articles	Percentage
Topics		Complex systems (ecosystems, forest system, climate change and pollination)	10	%31
		Sustainability issues and global problems (e.g., sustainable energy, environmental pollution, biodiversity, environmental problems)	15	47%
		Earth system science (water cycle, carbon cycle)	7	22%
Research Design		Quantitative Research Design (survey research)	3	9%
		Qualitative Research Design (descriptive)	10	31%
		Mixed Research Design (both qualitative and quantitative)	2	6%
		Intervention Study (experimental and qualitative)	17	53%
Intervention (Yes)		Yes	17	53%
Intervention (No)		No	15	47%
Data Collection	Qualitative tools	Interviews (structured, task-based, interviews with scenarios)	9	28%
		Written assessments (open-ended questions)	13	40%
		Case study analysis	2	6%
		Concept maps	4	12%
		Drawings	7	22%
	Quantitative tools	Multiple choice tests	4	12%
		Questionnaires (including Likert type questions)	4	12%
Sample		Primary school students	5	15%
		Lower secondary school students	13	40%
		Upper secondary school students	5	15%
		Student teachers	7	22%
		Undergraduate students	5	15%

Table 5. Systems thinking models used in the analyzed articles.

Systems Thinking Models	Number of Articles	Percentage
Dynamic thinking and cyclic thinking (Richmond 1991, 1993)	1	3%
Systemic reasoning framework (Chandler and Boutilier 1992)	1	3%
Systems Dynamics (Forrester 1992) and Systems' model of Booth-Sweeney and Sterman (2000)	4	13%
Understanding complex systems and emergent perspectives-Structure-Behaviour-Function Model (Hmelo-Silver and Pfeffer 2004; Hmelo-Silver et al. 2007, 2015; Hogan 2000; Wilensky and Resnick 1999)	8	25%
Systems Thinking Hierarchical Model (Ben-Zvi-Assaraf and Orion 2005)	9	28%
Stave and Hopper (2007)'s systems thinking model	1	3%
Arnold and Wade (2015)'s systems thinking model	1	3%
Heuristic-Structural competence model (Fanta et al. 2019; Schuler et al. 2018)	3	9%
Systems thinking as a key competency for sustainability education (Sleurs 2008; Wiek et al. 2011)	4	13%

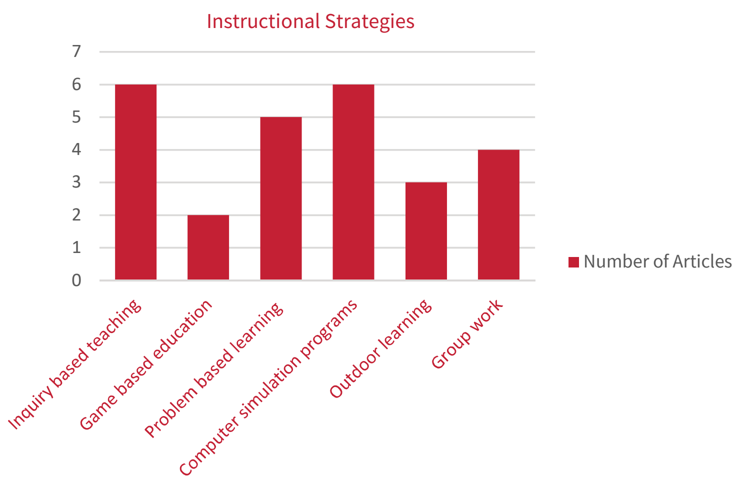

Figure 1. Instructional strategies used in the analyzed articles.

4. Discussion and Conclusions

The current problems we encounter are dynamic, complex and wicked sustainability problems, such as climate change, biodiversity loss, poverty, and the degradation of ecosystems (Chandler and Boutilier 1992; Wiek et al. 2011). Systems thinking is necessary to gain insight into these interrelated problems and to produce sustainable solutions (Capra and Luisi 2014). Systems thinking needs to be applied in science and sustainability education, in order to understand complex systems, such as ecosystems, socio-cultural and economic systems. Students can only actively participate in sustainability actions when these complex and dynamic relationships are understood (Riess and Mischo 2010). Therefore, systems thinking is a critical skill in science and sustainability education. Karaarslan-Semiz and Teksöz (2020) emphasized the importance of fostering pre-service science teachers' systems thinking skills so that they can contribute to developing the systems thinking skills of their future students.

Through this literature review, various topics, research methods and systems thinking models in the selected research studies were examined. Furthermore, the gaps in systems thinking research in the science and sustainability education context were explored. In the analyzed articles, the majority of the researchers focused on sustainability problems, ecosystems and the components of the earth system (particularly the water cycle). The earth system is a complex and dynamic system including interactions between the subsystems of the earth, and human activities impact the whole system (National Research Council NRC). Systems thinking is a good perspective to understand how the earth system works. Within the framework of National Research Council (NRC), it was emphasized that, before students proceed to secondary school, they should understand the major systems of Earth (geosphere, hydrosphere, atmosphere and biosphere). They should understand that there is always interaction among Earth's systems (Lee et al. 2019). For this reason, researchers have assessed the systems thinking skills of students in the subjects of water cycle, carbon cycle, ecosystems or climate system (e.g., Shepardson et al. 2014; Ben-Zvi-Assaraf and Orion 2010b). In the analyzed articles, sustainability problems were also used as a topic to determine the systems thinking skills development of students. A holistic view of global sustainability problems helps learners see the comprehensive picture and contribute to problem solving (Connell et al. 2012).

This literature review further revealed that researchers mostly conducted systems thinking studies with lower secondary school students. In the literature, there are some discussions about the age and grade level that are appropriate for teaching systems thinking skills (Lee et al. 2019). As the systems thinking is a higher order skill and difficult to foster, it is important to engage students in all age groups and grade level (Zohar and Dori 2003). Ben-Zvi-Assaraf and Orion (2010b) suggested that systems thinking skills can be taught and mastered at elementary school level.

Therefore, in the future, more studies relevant to systems thinking skills development can be conducted with elementary school students. In the current analysis, it was found that fewer studies focused on developing student teachers' and undergraduate students' systems thinking skills. Fanta et al. (2019) pointed out that studies on how to improve the systems thinking skills of adults are limited. Future systems thinking studies may be conducted in the higher education level. For instance, more intervention studies can be administered to foster the systems thinking skills of student teachers, as they can facilitate the learning environment to improve their future students' systems thinking skills. Science teachers and teachers linked to sustainability related subjects should have fundamental knowledge of system science and the ability to apply this knowledge to solve sustainability problems (Fanta et al. 2019). Therefore, in order to enhance the systems thinking skills of teachers, systems thinking should be integrated into teacher education programs. More research can be conducted to develop the systems thinking curricula in teacher education.

According to the data analysis, qualitative research tools including written assessments and interviews were mostly preferred to assess systems thinking skills. In addition to qualitative tools, multiple assessment techniques such as Likert type questionnaires, scales and two or three tier tests can be used to measure systems thinking skills. Brandstadter et al. (2012) argued that there is a need to develop appropriate measurement tools to assess systems thinking skills in educational studies.

In terms of research methodology, more than half of the examined studies included intervention studies and described different instructional strategies. The most common instructional strategies applied to foster systems thinking skills were inquiry-based teaching and computer simulation programs. Researchers also used problem-based learning and group work in the intervention studies. The least mentioned instructional strategies were outdoor learning and game-based education. Ben-Zvi-Assaraf and Orion (2010a) emphasized that inquiry-based outdoor and indoor learning activities can be effective to develop students' systems thinking skills. According to Fanta et al. (2019), problem-based instruction is an effective tool to develop a deeper understanding of complex systems. Jeronen et al. (2017) also emphasized that field work, field trips and problem-based activities are useful strategies to develop students' knowledge and interest in sustainability. Therefore, more intervention studies can focus on both indoor and outdoor learning strategies, to enhance the systems thinking skills of students.

Lastly, systems thinking models used in the selected articles were examined. In the published studies to date, different systems thinking models have been used according to the context of the research studies. The majority of the researchers used the systems thinking hierarchical model, complex systems and structure–behavior–function model as a framework. Researchers and educators agree that systems thinking is critically important to understand the complexity of the current problems and to propose solutions to them (e.g., Senge 1990; Meadows 2008; Arnold and Wade 2015). However, a variety of definitions of systems thinking can be found in the literature. Arnold and Wade (2015) emphasized that there is a need to create a precise definition of systems thinking, including, especially, three kinds of information, namely "purpose", "elements" and "interconnections". Previously, Meadows (2008) emphasized that these three aspects are the crucial components of systems thinking. In this study, it was explored that researchers particularly emphasized several components of systems thinking, which refer to interconnections, dynamic and cyclic relationships, feedback loops, hidden dimensions and time dimensions. Karaarslan-Semiz and Teksöz (2020) pointed to the affective dimensions that can be included in a sustainability education context. In future studies, systems thinking models may include more affective dimensions, such as building empathy with people and non-human beings and developing a sense of connectedness to nature. Affective or psychological factors can be considered in future systems thinking inquiries.

As a conclusion, in the analyzed articles related to science and sustainability education, it was found that researchers investigated different topics and used various measurement tools and research methodologies with different target groups from the primary level to higher education. This literature review revealed that the number of research studies conducted with primary, upper secondary school students and student teachers is limited. Future studies may be conducted with these target groups. In addition to qualitative research, quantitative and mixed research methods can be applied in the systems thinking research. Furthermore, curriculum analysis can be conducted to be able to integrate the systems thinking skills into curriculum programs. In teacher education programs, systems thinking courses can be designed to foster student teachers' skills and their pedagogical content knowledge to teach systems thinking to their students.

In the current times, we have complex problems that need urgent solutions. Developing the systems thinking skills of the individuals is extremely important to build a sustainable future. As this review revealed, more research is needed to nurture and evaluate students' systems thinking skills in science and sustainability education. Especially in disadvantageous regions, systems thinking oriented school programs can be designed to achieve equal and inclusive education and to improve learning outcomes for all individuals. Future studies may investigate the ways to integrate systems thinking into science education curriculum and design systems thinking integrated science and sustainability education programs.

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